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A review on applying ventilated double-skin facade to buildings in hot-summer and cold-winter zone in China

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ABSTRACT

The need to energy conservation and sustainable development in buildings is causing a new interest towards passive solar systems. Among them, double-skin facade (DSF) proves to be extremely attractive and promising. DSF is building envelope formed by two layers of different glazing facades which are separated by a ventilated air cavity. The cavity of DSF is used to collect or evacuate the solar radiation absorbed by the facades, thereby improving the thermal comfort and the indoor air quality while conserving energy for heating and cooling. Being a technique developed for colder climates, DSF has been widely applied in commercial buildings across Europe. Nowadays buildings with DSF also appear in the hot-summer and cold-winter zone in China where the weather conditions in summer seem to be not so good for the application. In fact, the thermal analysis of the DSF system is essential to its application in such hot-summer zone. This paper seeks to describe the existing main research methods on the thermal performance of DSF and the shading devices. Problems and possibilities are concomitant. Applying ventilated DSF with controlled shading device system would be a new efficient way for the commercial buildings in the hot-summer and cold-winter zone to meet the task of sustainable building design in China.

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1. Introduction

The need to energy conservation and sustainable design in buildings is causing a new interest towards passive solar system. Among them, double-skin facade (DSF) proves to be extremely attractive and promising. Double-skin facade, also called double-envelope facade, is multiple layer skins construction with an external skin (usually glass material), an intermediate space and an internal skin (usually glass material too) outside modern buildings. Beyond its good aesthetics, the DSF can collect or evacuate the solar radiation absorbed by the glazing facades and realize natural ventilation in the building, thereby improving the thermal comfort and the indoor air quality while conserving energy for heating and cooling. Being a technique developed for colder climate, the double-skin facade has gained wider acceptance and application in Europe, North America and Japan since 1980s. Recently, with the rapid economic development, more and more new buildings with double-skin facade have also appeared in the hot-summer and cold-winter zone in China, e.g. Shanghai and Hangzhou.

The hot-summer and cold-winter zone in China is the wide area situated among the Yangtze River Valley in the middle of China. This zone includes 16 administrative divisions such as Shanghai City, Hubei Province, Hunan Province, Anhui Province, Zhejiang Province, Jiangxi Province and so forth. The population of this zone is about one third of the whole national population. Its area is about 1,800,000 square kilometers while the GDP accounts for about 48% [1]. At the same time, the weather condition in this zone is very badly as compared to other areas in the same latitude among the world. In summertime the solar radiation is quite intense, and the average air temperature in July is 2 °C higher than that of other countries at the same latitude. In winter it is so cold that the average air temperature in January is 8–10 °C lower than that of other countries at the same latitude [1]. It is obvious that applying DSF techniques in this zone, where the weather condition seem to be not so good as that in the colder climate, may bring some new problems that could not be ignored. Experiments and simulations [1–3] show that in summertime, the intense solar radiation and low wind speed in night-time are the main disadvantages for using DSF techniques in this type of climate. Therefore the shading device system is usually situated in the channel of the double-skin facade to stop solar radiation in case of overheating.

In fact, building energy consumption of buildings with double-skin facade strictly depends on the thermal performances, especially the thermal heat transfer and solar heat gain which differ with seasons and latitude location. Literatures review shows that the majority of research is undertaken in cold and moderate climates. Very limited research on the thermal performance of double-skin facade has been undertaken under the climate condition as the hot-summer and cold-winter zone in China. This paper seeks to depict the main existing research methods on the thermal performance of DSF and the shading devices. The possibility and the new problems of using DSF techniques in hot-summer and cold-winter zones in China are also studies.

2. Working mechanism of double-skin facade

Double-skin facade is in fact becoming an important and widely used architectural element in office buildings, as they can provide numerous advantages beyond their good aesthetics. It is the building envelope formed by two layers (internal facade and external facade) of different glazing materials, that are separated by a ventilated air cavity (channel). The external facade layer provides protection against the weather and improved acoustic insulation against external noise. In normal use, shading devices such as blinds are installed in the cavity to protect the internal rooms of building from high cooling loads caused by solar radiation. The ventilated cavity is used to collect or evacuate the solar radiation that is absorbed by the facade. In cold weather, the DSF acts as a heat exchanger when sunlit so that the internal glass facade temperature nearly equals the room air temperature, which improves the thermal comfort. In hot summer, DSF can have a very low shading coefficient if the shading devices are appropriately placed since the majority of solar gains are removed from the window.

The modes of ventilation in cavity of DSF could be natural, forced or mixed. The natural ventilation of the DSF is based on the thermal buoyancy produced by the temperature difference between the exterior and interior cavity (separated by the shading devices), that is increased by the asymmetric solar radiation on and transmittance through the facades. Wind pressure can also influence the natural ventilation in the cavity [4,5]. The forced mode means mechanically ventilation in the cavity and the mixed mode is both natural and forced ventilation. According to the different ventilation modes and air flow path, the working modes for double-skin facade can be classified as three types, shown in Fig. 1 [6].

In the mode of type A, ventilation air from the room enters the double-glazed cavity, flows over the blind, and is, in some designs, exhausted from the building or returned through the ducts to the central HVAC system. For type B, the fresh air can be pre-heated in winter before entering the room. Type A and B are both mechanically ventilated facades, which can be integrated within the ventilation system of the indoor spaces, i.e. being part of Heating Ventilation and Air-Conditioning (HVAC) system of the building. Type C can also be called external respiration double-skin facade. This facade system is usually naturally ventilated. It can be used as a supply air window (i.e. supply fresh air into indoor space) for natural ventilation of room (when the window on the internal facade is open) or as an insulation envelope for a conditioned room (when the window on the internal facade is closed), which increases the thermal resistance [6]. The type of opening in the

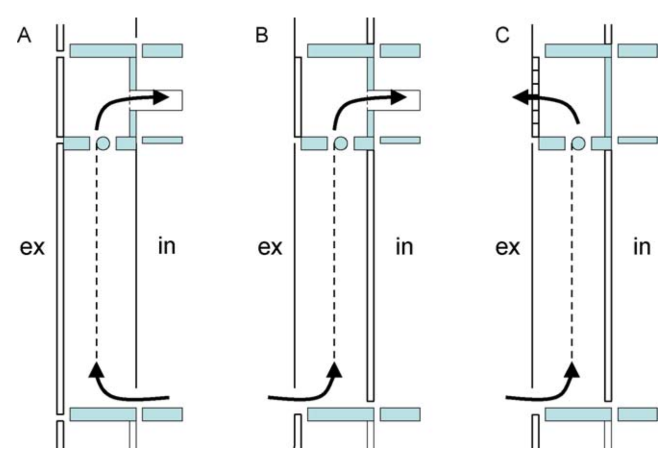

Fig. 1. Schematic representation of the working modes for double-skin facade [6].

cavity can be like a window for naturally ventilated facade or simply a slot for a mechanically ventilated facade.

A special ventilated window called airflow window (also called supply air window) are applied to residential buildings instead of double-skin facade. Airflow window are not as complicated as double-skin facade but can work like it. By introducing a further pane of glass which traps a blanket of air against the outside of the window, free or forced convection between two layers of glass called airflow cavities can be existed in the airflow window [7]. Recently a dual-airflow window with triple glazing is considered for residential buildings. This new type of airflow window works like a cross-counter flow heat exchanger. Thus it can conserve more energy than a single-airflow window [8].

3. New kinds of shading system in air channel of double-skin facade

The shading system situated in the channel of double-skin facade can protect the building from the solar heat gains in summer or play the role of the pre-heater for the ventilation air in winter. Roll screen and venetian blinds are two kinds of the conventional shading devices mostly utilized in the DSF. In hot period, the temperature of the shading devices is generally high because of the absorbed solar energy which will be transformed to the passing air by convection or by radiation to the neighbouring surfaces. Thereby the cooling load of the building is increased. In order to decrease this cooling load of the DSF building, many new ideas for shading system are considered.

3.1. Applying plants

Plants have the ability to dissipate absorbed solar radiation into sensible and latent heat. Especially due to the latent heat transfer the temperature of leaves is much lower than that of the blinds. Fig. 2 shows the scheme of the installation of plants in the DSF.

Stec's simulation on the double-skin facade with plants shows that the temperature raise of the plant was about twice lower than of the blinds for the same solar radiation in summertime. Additionally, the temperature of the plant never exceeded 35 °C, when the blinds temperature could exceed 55 °C [9].

3.2. Movable integrated glass-shading device

With the same aim of overcoming the overheating in warm summer, another new kind of double-skin facade is developed, as shown in Fig. 3, the external layer of which is made of a movable integrated glass-shading device.

In summer and most of the transition seasons (spring and autumn), rooms of this kind of buildings can obtain good natural ventilation by changing the shape of "the movable external layer" to an open configuration [10]. It can also avoid the summer greenhouse effect, which can greatly reduce the energy consumption of cooling. Meanwhile, it can still take advantage of the benefits of a typical double-skin facade in winter conditions.

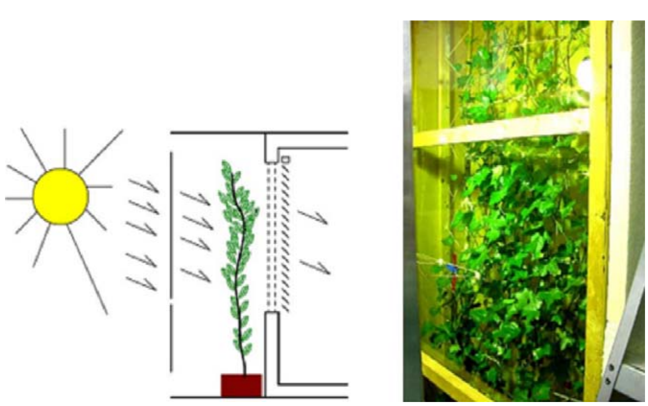

Fig. 2. Scheme of the installation of plants in the double-skin facade [9].

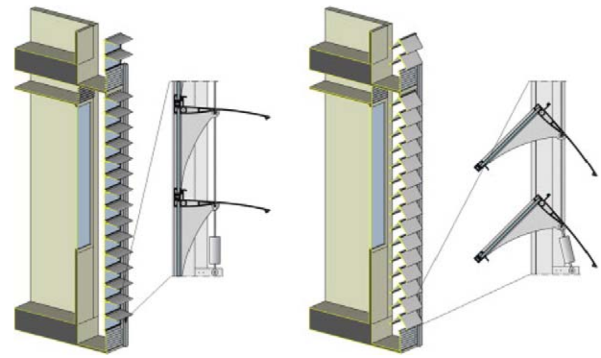

Fig. 3. Double-skin facade with an integrated movable shading system in winter and summer configurations [10].

4. Research methods on thermal performance of double-skin facade

4.1. Overall concept for modelling and simulation of the whole building with DSF

In order to make thermal comfort analysis and energy analysis for the buildings with DSF, it is needed to simulate their thermal performances. But it is not a trivial exercise to predict the performance of DSF. The temperatures and airflow result from many simultaneous thermal, optical, and fluid flow processes, which interact and are highly dynamic [11]. Especially, the airflow in the cavity is highly erratic, which make the problem more complexity.

According to Manz' paper [12], models on three levels are needed for reliable simulation of the thermal performance of the whole buildings with double-skin facade during summertime. These three models are spectral optical model (modelling the optics of the layer sequence of the double-skin facade), simulation model for DSF (modelling the thermodynamics and fluid dynamics of the double-skin facade) and building simulation model (modelling the building using a building energy simulation tool) in turn.

There are two stages of coupling for the whole building thermal simulation among these three levels. The first stage of coupling is to use of the absorptances obtained by the optical model to calculate heat sources in glass panes and on opaque surfaces of shading devices. These heat sources are subsequently implemented in the DSF simulation model. The second step is one-way static coupling between DSF simulation model and building energy simulation, i.e. the DSF simulation results were converted to coupling functions for subsequent implementation in a building energy simulation code [12]. The second step of coupling can be either static or dynamic. If building energy simulation and DSF simulation model are iterated several times at each time-step, the coupling is called dynamic.

The transmittances obtained by the optical model is used to calculate solar gains which is affected by the solar energy directly transmitted into the building through the double-skin facade. At each modelling level, input in the form of geometry, material properties, etc., is needed. Weather data for the specific building are also required to provide boundary conditions for both the DSF simulation and the building simulation.

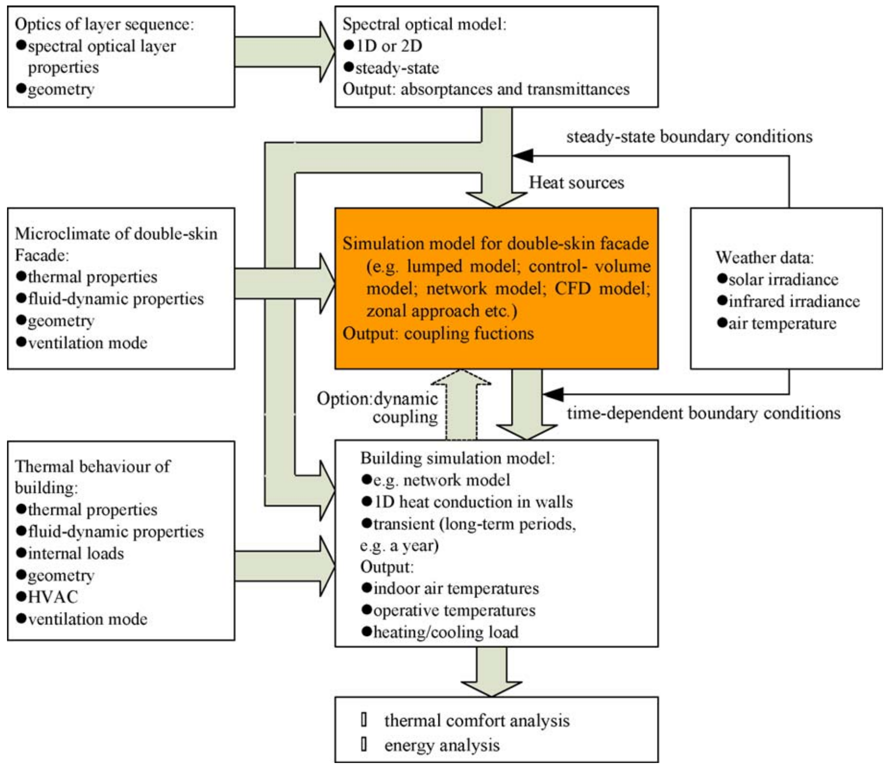

Fig. 4. Overall concept for modelling and simulation of the whole building with double-skin facade [12].

Fig. 4 illustrates the overall concept for modelling and simulation of building with double-skin facade [12]. As Fig. 4 shows, there are various experimental and numerical models used for studying the thermodynamics and fluid dynamics of the double-skin facade. The main simulation approaches for DSF will be introduced as follows. It should be noted that some research methods for the airflow window can also be applied for the DSF because the latter has very similar heat transfer and flow characteristics as airflow windows.

4.2. Overview on simulation models for double-skin facade

4.2.1. Lumped model

Lumped model is used for naturally ventilated double-skin facade. It uses a single node to represent each facade and cavity of the DSF system. This approach is based on a parameter estimation technique and calibrated on in-situ measurements. Park calibrates a lumped simulation model for a DSF system with controlled rotating louvers and ventilation openings [13]. The thermal behavior of the facades is simplified to a two-dimensional model. The exterior glazing temperature, the interior glazing temperature, the blind temperature, and the cavity air temperature are lumped in the vertical direction. There are several unknown convective heat transfer coefficients between the glazing facades and the air channel which should be estimated with parameter estimation technique, based on the extensive data points obtained from experiments [14]. The lumped model can represent the overall thermal characteristics of the DSF systems and determine optimal control actions.

4.2.2. Non-dimensional analysis

Non-dimensional analysis is proposed as a method to analyze energy performance of both natural and mechanical ventilated double-skin facade. When a process is described by dimensionless variables, these same parameters describe that process at all scales. Based on this concept, Balocco obtained 14 independent non-dimensional numbers by applying Buckingham theorem to describe thermal and energy performance of natural ventilated facades [15]. Balocco also used this non-dimensional analysis to study mechanical ventilated double-skin facade with shading device [16]. He provided 12 independent non-dimensional numbers to study thermodynamic performances of the mechanical ventilated facade system. In his work, the thermo-physical properties of fluid and facades except for air density are assumed to be constant. The flow in the air channel is also assumed to be steady.

The method can be used to know and compare different kinds of DSF system under different climate conditions, and can also derive useful design indications by varying some parameters using thermo-physical and climatic data easy to get [16].

4.2.3. Airflow network model

The airflow network model was applied for DSF equipped with venetian blinds [17]. In the network method, a building and the relevant (HVAC) fluid flow systems are treated as a network of nodes representing floor, ceiling, walls and system components, with inter-nodal connections representing the distributed flow paths associated with cracks, doors, pipes, pumps, ducts, fans, and the like [11]. A set of simultaneous, nonlinear equations are established on the conservation of mass for the airflow across each node. When it comes to the DSF system, both heat and airflows within the DSF system are considered as the thermal and air flow networks. The heat conduction, convection, absorption of solar radiation and long wave radiation and heat transfer are all derived from airflows. Therefore heat balances at every discrete node (e.g. the outside glazing skin, the outside air space, the shading device, the inside space and the inner glazing facade) can be obtained [17]. Many approximations are used to describe most of the pressure-flow relationships in these nonlinear equations when analyzing the natural ventilation in the DSF.

Therefore these nonlinear equations can be calculated very quickly on a personal computer by using an orifice flow approach based on estimates of pressure differences and discharge coefficients of openings [18].

Airflow network models are always coupled with energy simulation to evaluate the natural ventilation of office buildings with DSF [19,20]. It can also be applied to evaluate the energy performance of office buildings with DSF [21,22]. Till now, the network method is still suited for the "everyday" design support work [11].

4.2.4. Control volume approach

In the control volume approach, each facade of the DSF system is in turn divided into a number of control volumes (approximately 1 m high), which are only coupled due to the presence of the air channel. Only one-dimensional discretizations are used for the air channel and for each of the control volume (orthogonally to the facade). The mass flow rate for each control volume is assumed to be equal to the inlet mass flow rate. The temperature stratification in the DSF system is evaluated in the vertical direction [23,24]. The discrete equations are obtained for each control volume from the continuous governing equations using the finite volume method. The pressure distribution in the cavity for the evaluation of the airflow in the inner and the outer cavities is required as an input to the numerical solution. Fig. 5 illustrates the control volume model for the DSF system [25].

This approach has proved be a good compromise between accuracy (compared with the experimental results) and computing time [23].

4.2.5. Computational fluid dynamics method

Computational fluid dynamics (CFD) model is based on the concept of dividing the solution domain into sub-zones. Then, for each zone, the mass, momentum, and energy conservation equations are solved, utilizing the processing power of computers [26]. When it comes to the DSF system, the air channel and glazing facades are first discreted into two- or three-dimensional grids. Then the conservation equations for mass, momentum, and thermal energy are solved for all nodes of a two- or three-dimensional grid inside or around the DSF system [27]. In order to model convective heat transfer across the facades' surfaces accurately and ensure convergence of the equations, the aspect ratio of each cell in the grid must be small enough so as to capture boundary layer effects. The velocity and temperature fields in the cavity are governed by three basic equations: (1) the continuity equation (mass conservation) describes the interaction of orthogonal velocity components; (2) the motion equation (derived from Newton's second law) assumes that the variation of the momentum of a fluid cell is the sum of all forces applied on it; and (3) the energy equation (derived from the first law of thermodynamics) [28]. These basic equations are numerically solved at each point of the computational domain.

CFD techniques allow the determination of detailed temperature, velocity and pressure maps with little empirical information. With few reliable experimental data, many works on CFD techniques, such as FLUENT and PHOENICS, have been done to simulate the airflow and temperature distribution in the cavity of the double-skin facade. Furthermore CFD can also calculate the overall convective heat transfer coefficient between the DSF surfaces and the ventilated air channel [29] while other research methods usually treat this important coefficient to be a known parameter or make it determined during the numerical calculation using empirical equations.

4.2.6. Zonal approach

Jiru and Haghighat [30] employed the zonal airflow equation to calculate the airflow through the shading device and cavities. In the zonal approach, the DSF is divided into a number of control volumes, using cells usually larger than that in CFD applications. The mass and energy conservation equations are formulated for each cell without considering the momentum equations. Using the Power Law Model (PLM) defined by the pressure difference between neighbouring cells (zones), the mass flow rate through the venetian blinds and in the air channel in these conservation equations were computed. The convective heat transfer coefficients between the surfaces of the DSF and the cavity were estimated during the numerical calculation using empirical equations [30]. The zonal energy equations for DSF, including the absorbed solar radiation, long wave radiation exchange between layers, convective heat transfer between the cavity air

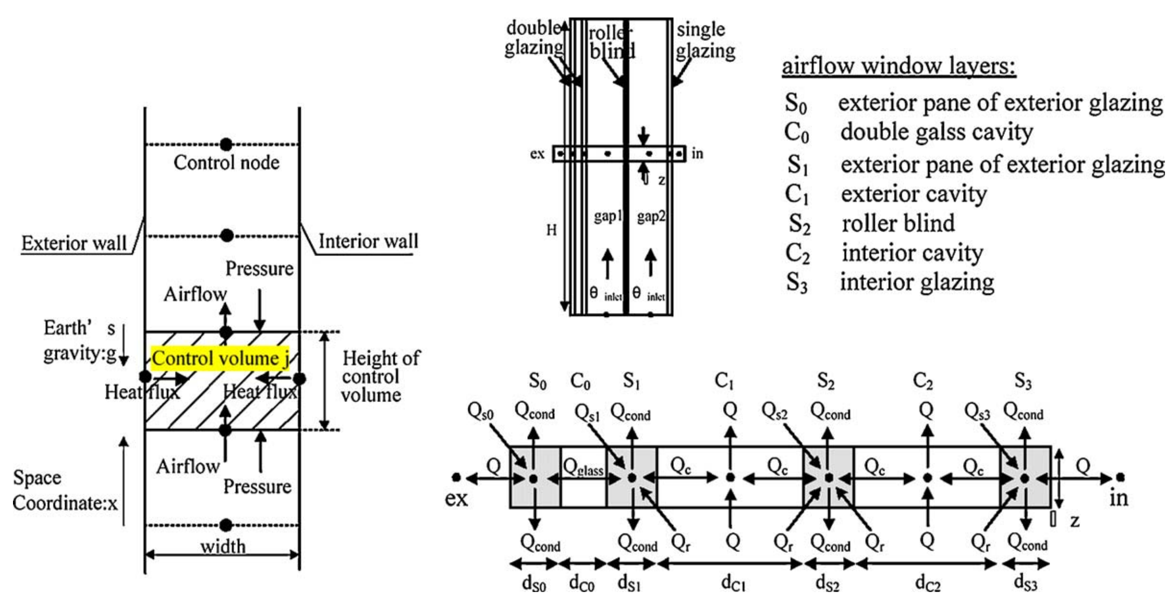

Fig. 5. Illustration of the control volume of double-skin facade system: (a) control volume of the air channel [23]; (b) control volume model for an airflow window with lowered roller blind (Q is the heat flux; Q_s is the absorbed solar energy; Q_c is the convective heat transfer; Q_{cond} is the conductive heat transfer; Q_r is the radiation heat transfer) [25].

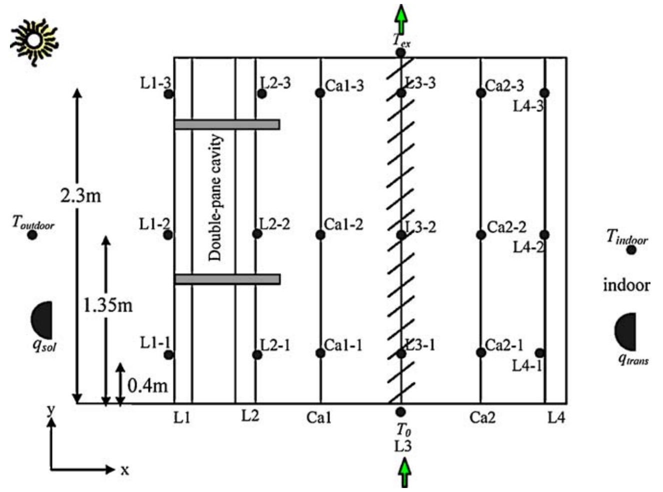

Fig. 6. Mechanically ventilated DSF: L1 is the exterior glass of the double-pane; L2 is the interior glass of the double-pane; L3 is the venetian blinds; L4 is the interior glass of the ventilated DSF; Ca1 is the outer cavity; and Ca2 is the inner cavity, T_o is the air temperature at the inlet, T_{ex} is the air temperature at the exit, T_{indoor} is the room air temperature, $T_{outdoor}$ the outside air temperature, q_{sol} is the total solar radiation, q_{trans} is the transmitted solar radiation, ● is thermocouple and ◖ is pyranometer [30].

and the layers, and conduction in the glass and shading device, was used to evaluate the temperature distribution in the DSF system. Fig. 6 illustrates the zonal model for the mechanically ventilated DSF with venetian blinds in the intermediate air channel.

The zonal models can computer the airflow and temperature distribution in a ventilated channel faster than CFD with more accuracy and detailed than lumped model.

4.3. Research on double-skin facade in China

As yet, no single software tool can accommodate all the complex processes occurred in double-skin facade. Literatures review shows that the majority of research is undertaken in cold and moderate climates. Only a few researches on the thermal performance of double-skin facades in hot-summer and cold-winter zones have been undertaken. Considering the great effect brought by the highly erratic airflow in the intermediate channel to the DSF, most of these researches on DSF in China are done with CFD [3,31–33]. Jiang used the CFD procedure "AirPak" to analysis the performance of airflow [31]. The results of simulated airflow performance are inputted as boundary conditions to "EnergyPlus" to calculate the heat gains through the double-skin facade. Chen used finite analysis calculation method to establish the Navier–Stokes momentum equations, the consecutive equations and the temperature field equations on the intermediate channel which is divided into a series of discretional units by using the theory of one-dimensional liquid flow [32]. Besides CFD, there are other analysis method which may be more simple. Cheng et al. setted up a thermal resistance network model to express the heat transfer in the DSF structure [34]. Steady state heat transfer equations are then established to determine the boundary temperature.

More reliable researches on the thermal performance of the DSF buildings are still worthy of doing for the hot-summer and cold-winter zone in China.

5. Research on shading device in air channel

The aim of using shading device is to stop solar radiation in the case of overheating. But they are also an obstacle to the airflow, and therefore they have an impact on the air velocity profile in the channel and on the convection heat transfer. In order to stop the solar radiation efficiently, the shading device system should be controlled according to the solar azimuth and altitude. Before optimizing the overall performance of DSF, the detailed thermal behaviour of the shading device should to be better understood. The size and position of the blinds, along with the slat tilt angle in the case of venetian blinds, are the main parameters needed to define the obstacle to the airflow.

Usually some of the research methods on thermal performance of double-skin facade (e.g. CFD simulation codes, numerical models also based on the transfer function concept, TRNSYS analytical models based on steady two-dimensional incompressible turbulent mixed convection flow in the transparent channel, low-Reynolds κ–ε turbulence models, control volume finite difference numerical integration techniques), are considered without activate shading device [35,23,24,36]. So that venetian or roller blind systems are taken and considered completely open or close and their influence on operating performance of the double-skin facade are neglected [16]. In fact the inclination angle of the venetian blinds is usually changed according to the incident of sunlight so as to keep back the incident direct solar radiation and control the daylight, thereby the airflow in the channel is also changed simultaneous.

Safer applied a porous media model for the venetian blind when he made the three-dimensional simulation with a CFD tool of the airflow in single-floor double-skin facade equipped with venetian blind. The homogeneous porous media can be divided into much bigger size meshes than that in the case of blind, and therefore the total number of meshes will decrease considerably [28]. Tanimoto employed the power law model (PLM) for calculating the airflow through the blinds using the network approach [17]. In his calculation, the total airflow in the outer and inner cavity is calculated using the power law equation but the airflow through each blind is approximated as a fraction of the total airflow rate. In order to estimate the convective heat transfer between the cavity air and the slats of the venetian blinds, Jiru also applied PLM in the zonal approach by assuming the slats as long horizontal cylinder in the ambient fluid. He used the Power Law Model (PLM) to calculate the airflow rate through the blinds and in the air cavities too. Gratia and Herde made [37] research on the natural ventilation in DSF with TAS software [4] to examine the influence of the position and the colour of the blinds on the cooling consumption of an office building with double-skin facade.

In conclusion, the dynamic convective heat transfer through the shading device should be considered with the airflow performance in the ventilated channel as both sides of the shading are heated or cooled. Comprehensive modelling work is still needed in order to understand the detailed impact of shading device on airflow in the channel.

6. Studies on applying DSF in hot-summer and cold-winter zone in China

Being a technique developed for colder climate using the idea of stack effect, DSF allows for the possibility of using natural ventilation techniques on buildings, even when subjected to great external noise and wind loads. In recent years, the application of DSF has gained popularity in modern building practice throughout the world even in Chinese cities such as Beijing, Shanghai and Hangzhou. The larger percentage of DSF buildings around the world is found in Northern Europe followed by Japan. However, there are still relatively few buildings in which DSF have actually been realized, and there is still too little experience of their behaviour in operation.

6.1. Problems for applying DSF in hot-summer and cold-winter zone

Pasquay monitored three buildings with DSF in Germany for 1 year or so. His long-term measurements show that DSF is reasonable to allow natural ventilation in high-rise buildings [38]. So Pasquay concluded that energy may be saved in specific locations compared to conventional solutions with full air-conditioning. But he also pointed out that DSF are not the best choice for every building in every location, and that the building must be considered independently. This opinion is supported by Gratia' study [21,39].

However, Germany is a typical European country where the climate greatly differs from that in hot-summer and cold-winter zone in China. As mentioned in the first section of this paper, in the hot-summer and cold-winter zone in China, the weather conditions is very badly as compared to other areas in the same latitude among the world. The disadvantages in summer, such as intense solar radiation, high outdoor temperature and always low wind speed, are not good for natural ventilation in double-skin facade.

6.1.1. Can double-skin facade suit for this hot-summer and cold-winter zone?

Yet very limited researches on the thermal performance of double-skin facade in such climate of this zone have been undertaken. The pros and cons for double-skin facade have been hotly debated by researches everywhere. The technical advantages for double-skin facade construction are: sun shading elements being protected in the facade space; noise reduction; possibility for night-time ventilation; functioning as a thermal buffer and as a pre-heater of ventilation in winter. On the other hand, there are several disadvantages related to double-skin facade: quite higher investment costs than that of traditional single-facade; the risk of overheating on warm sunny days; acoustics, moisture and fire safety. Besides these, other problems for applying DSF in hot-summer and cold-winter zone in China are as follows:

- Susceptibility to overheating during the summer months when peak outside air temperatures coincide with high solar gains;
- Very low night wind speed in summer [1] that are not good to realize the night-time natural ventilation in DSF;
- Very high outdoor temperature and intense solar radiation in daytime of cooling period which are obstacles for cooling the air channel only by natural ventilation.

Susceptibility to overheating when peak outside air temperatures coincide with high solar gains is usually considered the main drawback of the double-skin facade construction [12]. The solar radiation contributes quite more proportion of cooling loads to the building than that of the thermal conduction through the envelope in cooling period. While in winter the solar radiation is need to make air pre-heated. In fact, transmitted solar radiation is the most important contributor to indoor heat gains in hot-summer time.

6.2. Possibilities for applying DSF in hot-summer and cold-winter zone

Fortunately, the controlled shading devices in the cavity can improve the performance of the DSF in hot summer by reflecting large amount of the transmitted solar radiation [1,2,34]. Although in hot summer, the high temperature of the blinds will increase the cooling loads of the building, the risk of overheating can be reduced by providing good ventilation around the blinds. Meanwhile, if properly ventilated, the air flow in the cavity of DSF would take out a great deal of solar energy transmittance, which will greatly reduce the accumulation of the solar heat gains in the facades and the heat transfer into the room. The temperature of the outer glazing would increase as the effect of the solar radiation. But the airflow in the ventilated cavity can immediately take out the heat gain stored in the outer layer and increase the thermal resistance for the heat transfer to the inner layer. This can assure lower temperature of the inner glass. On the other hand, in winter, the intermediate cavity functions basically as a thermal buffer zone that provides passive heat gain from solar energy, which may offset the cooling loads in summertime.

Li made many experiments for different types of DSF with different ventilation modes in Wuhan which is a typical city in hot-summer and cold-winter zone in China [1]. The results shows that in summertime, the double-skin facade with venetian blind in the air channel can stop more solar heat gains than the single glass curtain wall with the same shading device if the venetian blind are activated and the channel is well ventilated. At last he recommended external respiration double-skin facade, i.e. type C shown in Fig. 1 with fan at the upper outlet, for this zone. Li' experiments also prove that the material and control of the shading system in the cavity are of great importance to the thermal performance of the DSF in cooling season. Besides experiments, theory analysis are also now done to the study the performance of DSF in hot-summer and cold-winter zone [31–33]. By using the building energy simulation procedure "EnergyPlus", Jiang calculated the annual energy consumption under the weather condition in Shanghai for the three kinds of building envelope: DSF, single glass curtain wall and conventional opaque wall with window, which are all situated southwardly. The heating load of the conventional opaque wall was 89.1% more than that of the DSF, while the cooling load of the opaque wall was 30% less than that of the DSF [31]. Thus the annual energy consumption for DSF buildings is the least among the three kinds of envelope if the DSF is properly managed.

The experiments and theory analysis both show the promising future for applying double-skin facade in the hot-summer and cold-winter zone in China. The current problem with double-skin facade is that the DSF buildings require adequate dynamic operation to reach their expected performance. Therefore it is of necessity to analyze the dynamic thermal performance of the DSF, which depends closely on the chosen ventilation means within its intermediate space [30], the performance and location of the shading system [37], the material of the glazing facades [5], the geometry size of the cavity [5,36] and the construction of the double-skin facade [6,39] and so on. This is still a challenge for the researchers.

7. Conclusions

Sustainable design in buildings are in demand to improve indoor living environment while conserving energy consumption. Ventilated DSF is a promising building envelope technique that may reduce solar heat gains in summer and provide thermal insulation in winter. In hot summer with intense solar radiation, heat gains is critical for the application in the hot-summer and cold-winter zone in China. The shading devices in the cavity, being activated, are needed to reduce transmitted solar heat gains. Ventilation in the intermediate channel is also intended to improve the thermal comfort conditions of DSF in hot summer. Thus ventilated double-skin facade may be the suitable envelope for the modern commercial buildings in this type of climate in China. It is in demand that the thermal performance of the DSF should be studies before applying DSF. There are now many research methods to simulate the complex dynamic thermal and fluid processes happened in the DSF. Nevertheless a suitable and reliable real-time simulation method for the DSF should also consider the effect of the controlled shading system in the channel, especially under the climate in the hot-summer and cold-winter zone in China. More researches on the thermal performance of the DSF buildings are still worthy of doing for the hot-summer and cold-winter zone in China. Energy conservation and sustainable design

in buildings would make the ventilated double-skin facade being the most attractive one among the building envelope in China.

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